



## FLAMMABILITY DURING WEIGHTLESSNESS

By John Howard Kimzey  
Manned Spacecraft Center  
Houston, Texas

FACILITY FORM 808	N66 29225	
	(ACCESSION NUMBER)	(THRU)
	17	(CODE)
	(PAGES)	33
	TMX-58001	(CATEGORY)
	(NASA CR OR TMX OR AD NUMBER)	

Presented to  
the Twelfth Annual Technical Meeting  
of the Institute of Environmental Sciences  
San Diego, California, April 13, 1966

GPO PRICE \$ \_\_\_\_\_

CFSTI PRICE(S) \$ \_\_\_\_\_

Hard copy (HC) 1.00Microfiche (MF) .50

ff 653 July 65

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

May 1966

## **FLAMMABILITY DURING WEIGHTLESSNESS**

**By John Howard Kimzey, NASA-Manned Spacecraft Center**

### **INTRODUCTION**

A series of experiments was conducted to learn the effects of weightlessness or "zero gravity" on a flame. This program was undertaken so that the seriousness of an accidental fire in a spacecraft may be evaluated, and means of controlling such an event may be developed. Many materials in a spacecraft are flammable. A fire could result from any number of malfunctions in the 100-percent-oxygen environment.

Only two instances were found in the literature regarding flammability in zero gravity. In 1956, Kumagai and Isoda reported on combustion of liquid droplets in a falling chamber. Data showed that as the droplet diameter decreased the flame diameter increased. Time was less than one-third second. Next, Hall in 1963 observed a burning candle in aircraft tests with intervals reported to be as long as 25 to 28 seconds. He concluded that the coloration change to deep blue, and some thermocouple data, indicated a somewhat hotter flame than in lg. Both of these earlier workers indicated that a steady-state condition existed.

### **ZERO-G FLAMMABILITY-PHASE I**

A comparison between a flame in lg and zero-g environments is indicated in figure 1. In lg burning of paraffin (shown in the left side) a series of events takes place simultaneously. Solid material is converted to a gas, thereby absorbing energy. The gas physically mixes with the surrounding atmosphere and, in chemically reacting with the oxygen, liberates energy. Hot gas products are formed: carbon dioxide, carbon monoxide, water vapor and a long list of minor constituents ranging from hydrogen to complex acids, alcohols, and other organic compounds. These products are formed through various intermediates including atoms and free radicals. The high temperature of these gases contributes to their low density. The gases rise out of the flame zone, allowing more oxygen to enter and mix with the fuel gases. Thus a steady state is possible and the flow-in can be equated to the flow-out. The

right side of figure 1 shows zero-g burning. This is an idealized concept based on experimental results. The sketch shows the flame as it reaches a maximum degree of burning. It should be emphasized that this condition is transitory. As may be seen in the films taken in a zero-g environment, there is a buildup of flame to maximum size and brilliance soon after ignition; then the flame quickly recedes and darkens. There are two reasons why the experimental flame in no case reached the total envelopment pictured here. First, the igniter localized the burning to a few spots, and second, the products of combustion tended to subdue the flame before it could envelop the fuel.

Several features of the zero-gravity flame are worth noting. The gas which is formed by an overheated material in zero gravity is ignited and burns in the oxygen with which it was initially mixed. The fuel-air ratio, therefore, changes during burning from lean to rich as the oxygen in the vicinity is used up. This occurs much more rapidly than the diffusion process can overcome. Eventually, oxygen starvation occurs and the flame begins to cool by radiation and conduction. What is left is a blanket of unburned flammable gasses adjacent to a solid or molten fuel which, in turn, is covered with a layer of combustion products, both solids and gases, having a very low oxygen content. The result is that the fire is diminished to the extent that light is no longer visible, indicating that steady-state burning was not reached. Thus, oxygen can be less than an inch away from warm flammable gases, yet unable to react with them. These conclusions were based on the pictures showing the flame darkening and diminishing less than 1.5 seconds following ignition. In the familiar 1g environment, things happen differently. The flame temperatures invariably increase over a short period of time to a maximum when steady state is attained. Zero-g burning is hampered by time limitations because only the fuel gases generated within extremely short periods of time can burn. The flame itself is apparently too weak in many instances to generate more flammable gases.

In several cases of paraffin burning, the light disappears for a few seconds and reappears as an accelerating force is induced to cause convection. This takes place when weightlessness ends due to contact with the aircraft. It is assumed when the light is out that the fire is out from the standpoint of emitting energy, as neither the Ektachrome nor infrared film used in the experiments show anything in these intervals. From the standpoint of chemical unbalance, however, the system is better described as dormant with the intermediate free radicals remaining where they were formed. With convection renewed, molecular oxygen reacts with these free radicals when the hot, light gases flow away from the fuel and the process resumes.

Table I is a list of the data pertinent to most of the tests shown in the motion picture film. A total of 26 burnings were photographed. Fuels included

spacecraft materials planned for Apollo, and paraffin, selected for its relatively simple chemical structure and kinetics. Atmospheres include pure oxygen, air, and other oxygen-nitrogen mixtures. Pressures varied from 5 psia, as used in manned spacecraft, to 14.7 psia. The nine burnings selected for this showing include styrene, white foam rubber, and paraffin as fuels. In all cases an excess of oxygen is present and in all cases the fuel was burning during the return to level flight.

The equipment designed for the experiments is shown in figure 2. These flammability chambers were designed for use in the KC-135 aircraft. Fifteen of these chambers were made so that they could be charged with a selected fuel and atmosphere under controlled conditions utilizing the in-flight time to the best advantage, and so that gas products could be analyzed later, after the flight.

The test chamber used in the first series of tests includes the following features: a shell of anodized aluminum with a volume of  $3/4$  cubic foot, which provides a region 10 inches in diameter for the flame; a pyrex window 1-inch thick to permit photographing the interior; and a fuel support which allows positioning of the fuel without obstructing the atmosphere or flame. This support is made of glass beads threaded on a wire. A filament, made of 20-gage nichrome wire, is positioned horizontally from two brass electrodes. Twenty-four volts dc pass through the wire to ignite the fuel. This voltage overloads the wire, causing a break in approximately 2 seconds, which opens the circuit. The fuel may be contacted at a single point or in several places. Each contact appears to start a separate fire, some of which join together. A grid located 5 inches behind the fuel provides one-quarter-inch parallel lines for reference. No supplemental light is used. In fact, the aircraft cabin is sometimes dark during the tests.

## FILM NARRATION NO. 1

Zero-gravity flammability was observed by using an aircraft at Wright-Patterson Air Force Base equipped for weightless flight. The first scene shows the interior of the C-131 with the lights on for this photography. The camera and ignition plugs of the control cable are shown being connected to one of the specially prepared flammability chambers. One of the engineers is shown making this connection. Now we see a sample float lasting 8 seconds. Some others lasted slightly longer with a maximum measured time in this series of 12 seconds.

The following are several tests showing ignition and combustion during weightlessness. These scenes are photographed at 200 frames per second and viewed in slow motion. The ignition wire is the horizontal member.

## STYRENE

First, styrene is ignited in zero g in 100-percent oxygen at a pressure of 5 pounds per square inch absolute. Note the fires starting at several points. The flame rapidly increases, and then begins to darken and diminish even before the wire breaks. The fire slowly spreads, causing some of the smaller fires to unite. Meanwhile, the burning rate continues to diminish as the time passes until the chamber strikes the inside of the aircraft cabin and the test is over.

## Foam Rubber

Foam rubber is seen next in the same atmosphere. It takes longer to ignite, and the ignition wire breaks less than 1 second following ignition. Here a very uniform flame corona is seen with flowing particles of carbon passing through a sharp interface in a completely random distribution. The dark shadow in the center of the flame is unburned fuel. Again, the corona diminishes and darkens before the weightless time is completed.

## Paraffin

Paraffin was used as a control fuel. Here we see paraffin ignited, weightless, in 21-percent oxygen at 14.7 psia. Note the heated gas quickly ignites, and then appears to go out. The wire can be seen to break and cool approximately 1/2 second following the start of ignition. The total real time before the flame reappears is 5.7 seconds. For the purposes of this showing, none of the blank film is deleted. Little information is available as to what is taking place during this interval of burning. No energy is emitted that is detectable in the Ektachrome film used here or in the infrared film used in the final scene. It is seen that the region containing the fuel is losing heat by both radiation and conduction. The nichrome wire is seen to darken and eventually become invisible. When the weightless time is up, by whatever direction or magnitude, the hot products of combustion leave the flame zone as fresh oxygen enters. In this series of tests the flame invariably reappeared as the force field was renewed so that in every case, except Teflon, the fuels were burning during the

return to level flight. Whether this is re-ignition because of the heat load or because of the gases remaining reactive or chemically hot - that is, containing a large number of free radicals with unpaired electrons that reacted with the molecular oxygen - is undetermined at this time. One other possibility is the presence of a "cool flame," but this is usually detectable by its deep purple color. Regrettably, the zero-g time was completed too soon, in this series of tests, for a fire once out to remain out. Several other paraffin fuels were similarly documented. Most of these tests exhibited the same self-extinguishment seen here.

Paraffin again ignites at the same total pressures as before except that this time pure oxygen is used. Here the corona is small as in the first two scenes, which also were photographed in a 100-percent-oxygen environment. The higher pressure of pure oxygen seems to make very little difference compared with the 5-psia pressure. The flame diminishes and darkens and appears to be out as before. The appearance of the flame at the upper portion of the fuel resulted from the location of the igniter wire, not from any induced motion at the time of ignition.

Paraffin is next ignited in an atmosphere of 50-percent oxygen-nitrogen at 10 psia. This is the same partial pressure of oxygen as in the first two scenes of styrene and foam rubber. The flame again has the darker, less defined corona which very rapidly diminishes, apparently because of the presence of the inert gas. The fire appears to be out but the package is struck and convection is resumed momentarily. Then weightlessness is resumed and again the fire appears to be out until a final impact shows its effect.

Another burning of paraffin in an atmosphere of 100-percent oxygen at 14.7 psia pressure is shown for comparison. This includes a few dramatic effects of impact on the molten fuel.

Paraffin in a 50-percent oxygen-nitrogen mixture at 10 psia is again ignited.

Infrared film was used in two burnings in an attempt to obtain a qualitative temperature measurement. This burning and the next uses paraffin in 100-percent oxygen at 5 psia. The pictures were taken at 100 frames per second. Thus viewing speed has been doubled to one-fourth real time for the two scenes. The same diminishing occurs until an acceleration is imposed as indicated by the vibration.

In this last test of paraffin burning in oxygen, the same atmosphere was used as before. Again the fire appears to be out in a very short time following ignition. This is especially significant in these infrared views.

## End of Film Narration

The temporary extinguishments seen in the film indicate that possibly there is a dormant, fairly cool pocket of chemically reactive gases remaining in the flame zone and igniting only if the oxygen contacts the fuel. In time, if left undisturbed, oxygen entering this zone slowly by diffusion could combine with the reactive products without raising the temperature. Gas samples were removed and analyzed in many of the tests. One gas of special concern was carbon monoxide. Carbon monoxide was not detected in samples burned in 1g, but was found in 3 of 18 of those zero-g tests which were analyzed for this gas. This is not surprising, however, when one considers the over-rich condition resulting from the zero-g environment.

## ZERO-G FLAMMABILITY-PHASE II

Table II gives burning rates of various materials investigated in the second phase of this work. Polymeric materials were selected as fuels. They represent electrical insulation in the case of the first four (neoprene, silicone, Teflon, and polyurethane) and a candidate space-suit material in the case of the last (dacron thread wrapped around polyurethane). All fuels are tubular in shape. Three test atmospheres were selected: ambient air, 5 psia pure oxygen, and 15 psia pure oxygen. One-g and zero-g data are compared.

The equipment in Phase II tests is basically the same as in Phase I except for the fuel configuration. Ignition is provided by a resistance wire closely wrapped around one end.

## FILM NARRATION NO. 2

Photography for Phase II is at 400 frames per second with Ektachrome-ERB film. Viewing at 24 frames per second results in slow motion at 1/17th real time.

### Neoprene

The first material is neoprene. Ignition occurred with "g" forces present, but weightlessness was achieved quickly. The nature of the heated material is such that boiling of the high viscosity fluid ejects gasses

intermittently, causing erratic burning. This makes it relatively difficult to tell from pictures alone when weightlessness exists. The burning rate is also affected by the resulting turbulence.

After an interruption of a few seconds, the burning is seen to continue. Note the solid particles leaving the flame zone. They may have been ejected by gas formation below the surface or by acceleration forces applied to the system. Without accelerometers, we can only say that stationary, floating particles are positive evidence of weightlessness.

A second interval is skipped in the viewing and we see the burning continue. Now weightlessness is up and the aircraft is leveling off. Measured burning rates under conditions of weightlessness are one-tenth of an inch per second, or half the propagation in lg.

### Silicone Rubber

A second material burned in 5-psia oxygen is silicone rubber. Note the ignition coil as it heats up. Approximately 1 second real time is required for ignition. Slight intermittent "g" forces are experienced again during the burning. Here the viscous bubbling of flammable gases is not as pronounced as before.

Note that the flame is barely visible and that the char which forms is more tenacious than seen earlier with the neoprene.

We should note that two different burning rates are involved. One is surface propagation. This is the one that is measured and recorded in table II. The other is burning normal to the surface. This latter combustion is slower, since it is affected by the ash formed and the blanket of gas products of combustion interfering with burning below the surface.

The burning is seen to continue 5 seconds later just before weightlessness ends.

Burning rates under conditions of weightlessness are one-tenth of an inch per second, as was the case with neoprene, compared to five-tenths of an inch per second in lg.

### Teflon

Teflon is ignited next in a 14.7 psia pure oxygen environment.



Ignition took place but the zero-g flame did not last more than seven-tenths of a second. Possibly more heat is needed to provide flammable gases than the flame produces.

### Polyurethane

Polyurethane rubber is seen next. Again intervals of weightlessness are periodically interrupted by the flammability chamber striking or brushing the aircraft. Again, the viscous bubbling is seen, as noted earlier in neoprene and silicone elastomers. This may be due to a non-uniformity of the solid, as well as the boiling resulting from the heat converting the fuel from the solid to the liquid to the gas phase.

The measured rate under weightlessness is again found to be substantially the same as with neoprene and silicone.

During the high-g pullout to level flight, we see the burning speeded up considerably. In lg, polyurethane burns at a rate of five-tenths of an inch per second.

### Dacron-wrapped Polyurethane

The last fuel included in Phase II is a simulated space suit made by wrapping a dacron (ethylene teneophthalate) thread around a polyurethane tubulation as used in the preceding section of this narration.

Ignition occurred in zero g with an acceleration encountered immediately. An unusual flame pattern can now be seen, resulting from changing "g" forces.

Weightless burning is seen after a few seconds. The bubbling noted earlier in the polyurethane test is again seen. A difference, however, is the soot formed by the combustion of dacron and seen floating inside the flammability chamber.

The zero-g burning rate is noted to be one-tenth of an inch per second, compared with five-tenths of an inch per second in lg.

End of Film Narration

## CONCLUSION

The following is concluded from these tests:

1. Ignition during weightlessness is essentially unchanged compared with lg.
2. Burning rates are reduced to approximately one-tenth of an inch per second.
3. Self-extinguishment can take place for some fuel-atmosphere systems.
4. Introducing an acceleration renews convection promptly.
5. A gas interface exists at the edge of the corona. This implies a phenomenon analogous to surface tension, with characteristics varying according to the presence of inert gases.

## ACKNOWLEDGEMENT

The assistance of F. A. Schreihans, D. E. Drysol, and G. R. Edgell of North American Aviation Inc., S. & I. S. D., was gratefully appreciated in Phase II work as well as Dr. W. R. Downs, C. H. Eldred and C. W. Norris of the Manned Spacecraft Center for both phases.

## REFERENCES

1. Kumagai, S. and Isoda, H.: Combustion of Fuel Droplets in a Falling Chamber. Sixth International Symposium on Combustion, 1956, pp. 726-731. Reinhold Publishing Company.
2. Hall, A. L.: Observations on the Burning of a Candle at Zero Gravity. Bureau of Medicine and Surgery Project MR005.13-1002, Research Report No. 5 of February 26, 1964, U. S. Naval School of Aviation Medicine, Pensacola, Florida.

# OXYGEN ATMOSPHERE

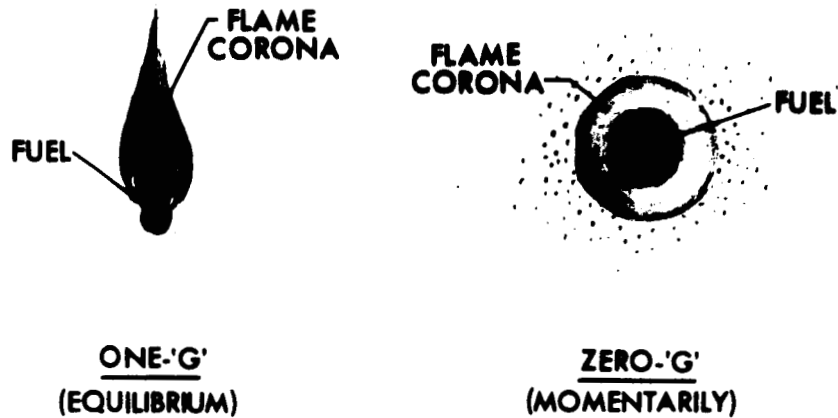


Figure 1. - Comparison of fuel burning at 1g and zero g.

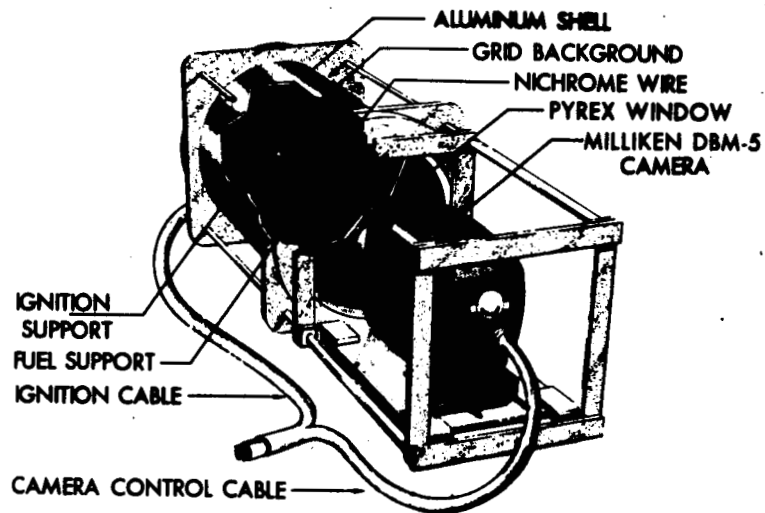


Figure 2. - Zero-g flammability chamber.

**TABLE I. - ZERO-G BURNING EXPERIMENTS**

<b>Reactor</b>	<b>Fuel</b>	<b>Weight, grams</b>	<b>Atmosphere, psia</b>	<b>Zero-g time, sec</b>	<b>Photog- raphy</b>
16	Styrene	1.0003	O <sub>2</sub> -5	NR	Color
15	Foam rubber	0.2706	O <sub>2</sub> -5	6	Color
35	Paraffin	0.7213	21%-O <sub>2</sub> -14.7	10	Color
19	Paraffin	0.1084	O <sub>2</sub> -14.7	5-8	Color
56	Paraffin	0.1636	50%-O <sub>2</sub> -10	7-12	Color
28	Paraffin	0.1244	O <sub>2</sub> -14.7	5	Color
36	Paraffin	0.1551	50%-O <sub>2</sub> -10	3-8	Color
22	Paraffin	0.1524	O <sub>2</sub> -5	NR	IR
10	Paraffin	0.5680	O <sub>2</sub> -5	3	IR

Note:

1. Pressures are nominal.
2. For percentage O<sub>2</sub> given, consider balance dry nitrogen.
3. For 21 percent O<sub>2</sub> given, atmosphere was air of 60 ± 10 relative humidity.
4. NR = not recorded.
5. IR = infrared.

TABLE II. - BURNING RATES IN 1g AND ZERO-g

Fuel <sup>1</sup>	Rate of burning, inch per second					
	1g			Zero-g		
	15 psia air	5 psia oxygen	15 psia oxygen	15 psia air	5 psia oxygen	15 psia oxygen
Neoprene	0.0	0.2	0.4	-	0.10	-
Silicone	0.04	0.5	1.1	0.0	0.08	-
Teflon	0.0	-	-	-	0.00	-
Polyurethane	-	0.6	0.7	0.0	0.08	0.15
Dacron <sup>2</sup>	-	0.6	0.7	-	0.08	0.15

Note:

1. Fuel is tubular (#10 AWG I. D.) and threaded over a steel or ceramic mandrel.
2. Dacron thread is wrapped around polyurethane.
3. Ignition is provided by electric resistance coil.
4. Temperature of atmosphere is  $65 \pm 5^{\circ}$  F.